Efficient Photon-Pair Generation via Quasi and Extended Phase Matching Devices Based on Spontaneous Parametric Downconversion

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論 文 内 容 要 旨

In quantum processing applications, Spontaneous Parametric Downconversion (SPDC) process has been a key element as heralded single photon source and entangled photon source. Optical quantum system can take advantage from well-developed modern optical communication systems for long distance transmitting and implementing quantum cryptography based on it, also due to the features of easy generation and detection of photons make optical quantum application protocols devoting much attentions nowadays, e.g. optical linear quantum computing, quantum communication, quantum metrology. In order to implement those protocols, we need photon sources that fit our needs, hence very actively developing of sources for generating polarization entanglement using photons via SPDC and heralded frequency uncorrelated single photons. However, they all surfer the imperfect performance and low efficiency. For future optical quantum applications, we expect highly efficient optical quantum system (include single photon source, quantum interference units and single photon detectors) with promising performance. SPDC has the benefits of easy setup, high efficient, high flexibility, thus it is the most commonly used scheme for photon generation. We combine SPDC with techniques like Quasi Phase Matching (QPM) and Group Velocity Matching (GVM) for photon generation which is aimed to future optical quantum applications. In my Ph.D. projects, we have developed SPDC process based devices for polarization entangled photon pair generation and frequency uncorrelated photon pair generation. Our aim in this work is developing photon sources that suitable for future optical quantum applications in terms of high efficiency and high spectral purity.

Polarization entangled photon sources play an import role in understanding quantum mechanics, furthermore it is also essential importance in quantum information communication technologies, quantum teleportation, quantum computation, and quantum cryptography. The most established method so far used for the entangled photon generation is SPDC process in nonlinear crystals, such as $LiNbO_3$ (LN) and $KTiOPO_4$ (KTP). In recent time the technique of QPM together with waveguide structures has been developed as a fundamental tool for photon generation, for instance, PPLN (periodically-poled LN) and PPKTP has been used as efficient sources for preparing entangled photons at telecom band. We proposed a post-selection free scheme for polarization entangled photon generation by utilizing type-II PPLN having two poling periods with different period length, the technique has recently been demonstrated in bulk PPLN with a series poling periods structure, also Harald Herrmann, etc. had exploited this method in their PPLN waveguide with a interlaced poling periods structure. We developed a waveguide device consisting of ridge waveguides with two sequential poling periods in each waveguide as a flux, simple and efficient entanglement source. Our device generates single spatial mode polarization-entangled photon pairs at two (nondegenerate) wavelengths in the telecom band with high generation rate, moreover, the obtained quantum state exhibits high fidelity compared to an ideal bell state. We worked together with the waveguide manufacturer Oki electric industry to implement our design shown in Figure 1, this rough sketch gives a schematic view of our waveguide structure. Our waveguide consists of MgO-doped $LiNbO_3$ core adhered on

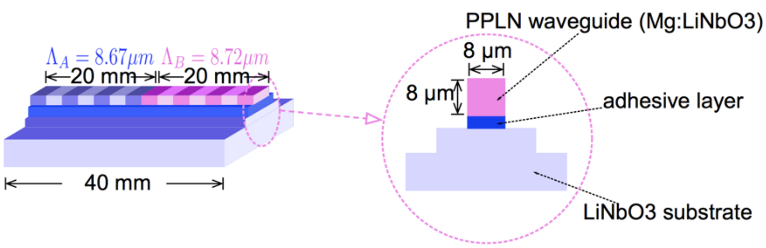
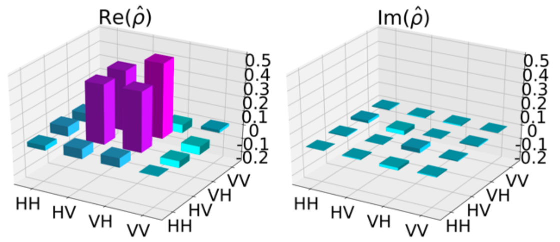


Fig. (1) Fig.1 Schematic view of the waveguide. A ridge waveguide consists of a MgO-doped LiNbO3 core adhered on a LiNbO3 substrate.

a $LiNbO_3$ substrate in order to guide both orthogonal polarization modes. Our waveguide contains two parts with different poling period Λ_A = 8.67 μm, and Λ_B = 8.72 μm for two Type II SPDC process with length 20 mm respectively. MgO-doped $LiNbO_3$ has a higher refractive index so it forms a waveguide core with 8 μm × 8 μm section size. In our particular device, Λ_A =8.72 μm and Λ_B =8.67 μm, each of which has the length of L=20 mm. The signal and idler photons have horizontal (H) and vertical (V) polarizations, respectively. Using this device, we expect that the first (second) section emits photons with the wavelength λ_1 in the H (V)-polarization and λ_2 in V (H)-polarization. To do so, we tune the emission wavelengths of signal and idler photons by tuning, for instance, the device temperature. The generated state results in the superposition of the photon pair states emitted from the two sections. Thus, if we label the photons in terms of their wavelength, the generated state is polarization-entangled so that

$$|\Psi\rangle = 1/\sqrt{2}(H\rangle_1|V\rangle_2 + e^{i\psi}|H\rangle_2|V\rangle_1) \tag{1}$$

where the labels 1 and 2 refer to photons of λ_1 and λ_2, respectively, φ is the relative phase originating from the difference in birefringent group delay between the two photon pair states. Signal and idler photons emitted from our device were pumped by a CW laser (wavelength: 772 nm), An InGaAs spectrometer followed was used for observing SPDC spectra. We see that the signal photon emitted from one section and the idler from the other section have the identical wavelengths at 16°C. At this temperature, the emission spectra for signal (H) and idler (V) photons are almost identical, with having two peaks located at λ_1 =1533 nm and λ_2 =1556 nm. Thus, the condition to obtain the polarization entangled state (Eq. 1) is fulfilled. In order to evaluate the performance our entangled photon source, we carried out three experiments. In those experiments a LN crystal (length = 20 mm) has been used as a compensator for compensating the longitudinal walk-off that otherwise causes distinguishability between the two terms given in Eq. 1, thus degrades the entanglement. Before the detections, pump light was blocked by a long-pass filter after which signal (λ_1 = 1532 nm) and idler (λ_2 = 1556 nm) photons are then separated in terms of their wavelength at a dichroic mirror (DM), which transmits the shorter wavelength (λ_1 = 1532 nm) photons and reflects the longer wavelength (λ_2 = 1556 nm) photons. With such simple setup we described, a polarization entanglement source can be easily obtained, and in following experiments we show our source create high quality entanglement, yet with high generation efficiency. In the experiment of generation efficiency measurement, we have observed a very high generation efficiency $n_{eff} = 1\times 10^7$ pairs/sec/mW. Comparing it to the previous work with PPLN bulk crystal, we obtained 100 times higher efficiency due to our waveguide structure. In order to verify the polarization correlation of our generated state, we carried out a polarization correlation measurement of signal and idler photons in the linear polarization bases, i.e. horizontal, vertical and ±45° directions. For nonclassical correlations, we should be able to observe correlation in all the orthogonal bases. In this experiment we used sets of half wave plates for rotating the polarization directions, also a pair of bandpass filters (FWHM 0.1 nm) here were used for eliminating the unwanted frequency components. In polarization correlation measurement experiment we observed over 0.92 visibility for both horizontal-vertical base and ±45° base, which implies the polarization correlation is nonclassical, we witnessed quantum correlation via our device. We also rivaled it previous research and found our device also provide a good performance. To fully characterize the quantum state, we carried out quantum state tomography measurement, in this experiment we project the quantum state we want to measure to all sets of polarization bases, i.e. linear and circular polarization combinations. With this knowledge, we can reconstructive the density matrix of the measured state (Fig. 2).



(a) Real part of density matrix (b) Imaginary of density matrix

Fig. (2) Real (left) and imaginary (right) parts of the density matrix reconstructed by quantum state tomography.

We use Fidelity obtained from our density matrix to verify how close it is to an ideal Bell state:

$$F = \mathrm{Tr}(\sqrt{\sqrt{\rho_{\mathrm{bell}}}\rho_{\mathrm{exp}}\sqrt{\rho_{\mathrm{bell}}}} \qquad (2)$$

And our fidelity F = 0.92 shows the generated state with our waveguide device is very close to an ideal Bell state.

Photon sources for optical quantum applications like optical quantum computation, boson sampling, quantum metrology, and quantum repeater, those applications highly rely on the performance of nonclassical interference between individual photons. High visibility of interference between photons requires photons be completely indistinguishable in all the degrees of freedom. By studying the refractive index of KTP, it has been known that KTP can be used under group velocity matching condition at telecom wavelength, in this case, joint spectral distribution of phase matching function has a -45° angle. Later on, the -45° angle of phase matching function has been confirmed by experiment, it implies we can achieve a spectral uncorrelated photon pair generation by adjusting pump pulse width. However, the purity of those experiments is limited, that is due to the sinc function shape of phase matching function. A sinc function like phase matching function introduced many unwanted frequency components, hence the reduction of purity. A solution for this kind of problem is generating a Gaussian-shape phase matching function. Currently, there are two schemes for the generation of a Gaussian shape phase matching function of SPDC process. As a visiting student, I worked in Franco Wong' group with their unique designed cpKTP device. This cpKTP crystal has a modified duty cycle which provides a Gaussian shape phase matching function. It has the potential for generation frequency uncorrelated photons with very high purity. n order to verify the unique Gaussian shape phase matching in our cpKTP crystal, we carried out different frequency generation (DFG) measurement. In our typeII SPDC device, the horizontally polarized pump light splits into signal light with horizontal polarization and idler light with vertical polarization. We used a CW laser with wavelength fixed at 791 nm and power fixed at 100 mW combined with a wavelength tunable centered at 1582 nm as probe laser. Pump laser has horizontal polarization and probe laser has vertical polarization. By scanning the probe wavelength, we recorded the horizontally polarized signal light intensity. Comparing the experiment data to a Gaussian fitting, we confirmed by modifying duty cycle, the phase matching function is fairly close to Gaussian shape with very few unwanted frequency components. Generation of spectrally uncorrelated photon pair with very high purity is the main purpose of this work, so it is important for us to verify the spectral purity by a joint spectra measurement. In experiment crystal temperature was still maintained at 18 °C, pump laser was 100 fs pulse laser. In order to tune the bandwidth of the laser pulse, we built a 4f system, in which a pair of gratings and a pair of lenses with focal length f = 20 cm were used, a tunable rectangular aperture at the center of 4f system acted as a tunable bandpass filter. Generation of frequency uncorrelated photon pairs with high purity via cpKTP. We also used a dispersion spectrometer for characterizing wavelength information. A Bragg grating fiber based dispersion module with the dispersion of 1882 ps/nm at 1582 nm, which is equivalent to ~ 100 km fiber dispersion, however, this dispersion module only has 3 dB loss. Combining our SNSPD detectors with 200 fs time resolution, we are able to verify wavelength information with 0.1 nm. We use the scheme of Schmidt decomposition to verify the spectral purity in this experiment.

$$|\Psi\rangle = \sum c_k |a\rangle|b\rangle \tag{3}$$

Where ψ is a pure state, A and B are the index for two subsystems, c_{jk} is Schmidt coefficients. Therefore spectral purity is:

$$P = 1/K = \sum c_k^4 \tag{4}$$

P is spectral purity, it is numerical verification of how many spectral modes contains in a state. With infinite modes number $K \rightarrow \infty$ and $P \rightarrow 0$. In the case of frequency uncorrelated state, we have only one spectral mode, hence $K \rightarrow 1$ and $P \rightarrow 1$. Using this method, we verified our joint spectra and the results are shown in Fig. 3 The highest purity we can obtain from this source is 0.99, that is also the highest purity ever reported.

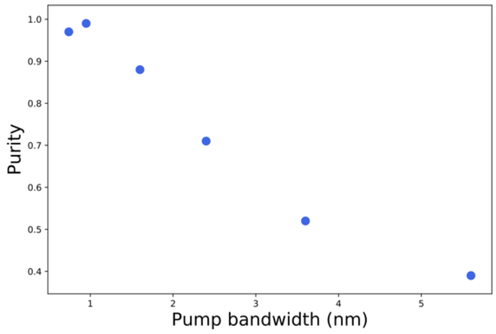


Fig. (3) Spectral purity with different pump bandwidth. correlated and anti-correlated joint spectra have lower purity, the highest purity was obtained from circular shape joint spectrum.

However, the cpKTP device suffers low generation efficiency. With the growing interests of highly efficient pure heralded single photon generation, many groups have reported waveguide based PPKTP device offers higher generation efficiency. However, unlike PPKTP, in those reports, joint spectra had an elliptical shape due to the changing of GVM caused by the shifting of refractive index. In this work we also developed a frequency uncorrelated source based on waveguide. According to our simulation result, waveguide device dose not satisfy group velocity matching condition at telecom wavelength perfectly. We experimentally confirmed it by measuring the SPDC spectra which shows the phase matching function does not have a -45 °angle. Nevertheless, this device can be used as spectrally pure heralded single photon. Our PPKTP waveguide is manufactured by AdvR inc. It a 10mm long chip with channel waveguides. Those waveguides are set in six groups, 33 waveguides in total. This PPKTP waveguides are specifically designed for telecom wavelength with the poling period of the entire waveguide chip is 136.986um. From the simulation and SPDC spectra measurements, we know that because of the exchanged Rb ion in the waveguide core and the structure dispersion of the waveguide, the refractive index has been shifted compare KTP bulk crystal, therefore, the estimated wavelength that satisfied GV condition in our PPKTP waveguide has shifted. In order to verify the spectral purity, we also carried out joint spectra measurement as well. The highest purity we found in this waveguide device is P = 0.88. We consider this imperfect purity is caused by side-lobes introduced by sinc shape phase matching function, all unwanted frequency introduced by non-uniformed effective refractive index due to imperfect manufacture. We also noticed signal and idler photon are not degenerated, meaning single and idler photon is in their own single frequency modes, however, the frequency mode of signal photons is different from frequency mode of idler photons. we found the generation of our waveguide device is 4.7 × 106 pairs/sec/mW, it is almost 100 times higher than PPKTP bulk crystal. Hence this source is not suitable for applications like creating NOON state, on the hand it is a capable source for heralded single photon source. So far, we have used the most common method for evaluating spectral purity which is Schmidt decomposition of a joint spectra. However, this method has its limitations on this task. First one is theoretically Schmidt decomposition should be performed on join spectra in terms of amplitude, nevertheless, photon detectors can only detect the intensity of light, meaning not only all the phase information have been lost but also main peak and side-lobes would be more distinct during the process. The second reason is joint spectra measurement can only measure a finite wavelength range, which is to say all the frequency components beyond measurement range are eliminated. It is equivalent to applied a bandpass filter. In the aspect of photon number distribution, SPDC emits photons into a thermal distribution. However, in the case of frequency correlated photon generation, SPDC process generates photons with multiple frequency modes, since each mode has a thermal distribution the combination of all the frequency mode yields a random photon number distribution which behaves like coherence light. Therefore, we can distinguish frequency correlated state and frequency uncorrelated state by investigation of photon number distribution. In the experiment, we use intensity correlation measurement which also is called $g^{(2)}$ measurement for characterizing photon number distribution. What is important for us is the zero delay term $g^{(2)}(0)$. for the light has a thermal photon number distribution, $g^{(2)}(0)$ is predicted to be 2, in contrast, when the light behaves like coherence light that has a random (Poissonian) photon number distribution, regardless of time delay τ between two pulses, $g^{(2)} = 1$. In this experiment, we use a PBS to separate signal and idler photons. Since the pump laser has the repetition frequency 80 MHz, on the other hand, our detectors can only work at 4 MHz, we used a frequency divider for generating trigger signals for our detectors. We fed signal and idler photon separately into single mode fibers, by using a fiber base BS we verified the autocorrelation terms as well as cross-correlation terms. We can verify spectral purity by:

$$P = g^{(2)}(0) - 1 \tag{5}$$

The highest purity obtained using this method appeared different result, for signal photons we have the maximum purity of 0.80±0.03, meanwhile, the maximum purity for idler photons is 0.72±0.05.

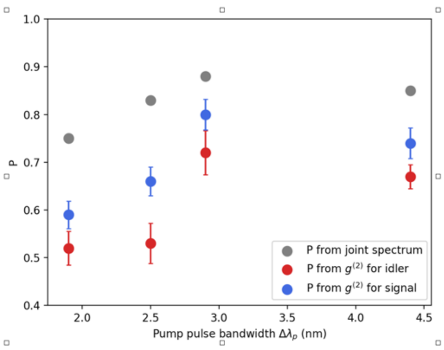


Fig. (4) Spectral purity obtained from Schmidt decomposition (grey dots); intensity correlation measurement for signal beam (blue dots); intensity correlation for idler beam (red dots).

Purity obtained by three measurements have the same trends according to pump pulse band width. g(2) measurements offered a lower purity as we expected.

Firstly, we developed a typeII SPDC PPLN waveguide device which can be operated at telecom wavelength based on quasi-phase matching technique. Our PPLN device contains two sections with poling period Λ_1 = 8.72 μm and Λ_2 = 8.67 μm. It is designed for efficient polarization entanglement generation. Comparing with previous works we observed much higher generation efficiency $n_{eff} = 1\times 10^7$ pairs/sec/mW. We carried out a polarization correlation measurement and quantum state tomography measurement for characterizing the generated state. As the result of polarization correlation measurement, both horizontal-vertical base and ±45° base have the visibility over 0.92, it implies the polarization correlation is nonclassical. Quantum state tomography measurement shows the generated state is very close to an ideal Bell state with fidelity F = 0.92. Secondly, as a visiting student in MIT, I worked with Franco Wong's group, by measuring the phase matching function of their modified duty cycle cpKTP device, we found it owns a Gaussian shape phase matching function, it has the potential of a generation of high purity photon pairs. In order to evaluate the spectral purity, we carried out a joint spectra measurement, as we expected we obtained the highest purity P=0.99. However, due to the special duty cycle design, the generation efficiency became lower than conventional PPKTP device. In the third project in order to increase generation efficiency, we also developed a spectrally pure single photon source based on waveguide structure. The generation efficiency of this device is 4.7×10^6 pairs/sec/mW which is about 100 times higher than PPKTP bulk crystal. However, there have been reports showing that no perfect GVM condition in PPKTP waveguide, we confirmed it by studying refractive index in a waveguide with simulation and experimental investigation of SPDC spectra. Furthermore, we used two methods for verifying spectral purity, (1) Schmidt decomposition of a joint spectrum. (2) Intensity correlation measurement. We found even though there is no perfect GVM in the waveguide, we can still obtain P=0.80±0.03pure single photons. We consider this is a device suitable for the future quantum application like optical linear quantum computation.

論文審査結果の要旨

近年，量子情報通信技術で重要なリソースである，量子もつれ光子や伝令付単一光子を生成するための光子対生成技術が急速に進展している。自発パラメトリック下方変換（SPDC）は，信頼性の高い光子対発生方法として広く用いられているが，周期分極反転（PP）素子を用いた疑似位相整合と導波路構造の導入による高効率な光子対発生技術や，拡張位相整合（位相整合における分散を考慮する技術）を利用した周波数相関の制御技術等，SPDC を利用した新たな光子対生成技術が注目されている。本研究では，これらの新たな技術を用いた高効率・高性能な光子対発生技術の開発を目的として，(1)二周期分極反転導波路素子を用いた高効率量子もつれ光子対発生，(2)特殊な分極反転プロファイルをもつ疑似位相整合素子を用いた周波数無相関光子対発生，(3)拡張位相整合導波路素子を用いた高効率周波数無相関光子対発生に関する研究開発を行なった。本論文はその研究成果をまとめたもので，全編6章よりなる。

第1章は序論であり，研究の背景と目的について述べている。

第2章では，本研究の基礎となる理論および背景知識について記している。まず，単一光子および伝令付単一光子の性質について述べた後，SPDC，疑似位相整合および拡張位相整合による光子対の発生原理について解説している。

第3章では，二周期分極反転導波路素子を用いた高効率量子もつれ光子対発生の実験結果について論じている。2つの異なるPP構造が直列に配置されたPPLN（PP-$LiNbO_3$）導波路素子を用いて，偏光に関する量子もつれを有する光子対を生成し，その生成効率および量子もつれの状態を定量的に評価した。その結果，高い忠実度（0.92）をもつ量子もつれ状態を，同じ PP 構造をもつバルク結晶に比して約 100 倍の生成効率（1×10^{10} $s^{-1}W^{-1}$）で生成できることを明らかにした。単純な構造で安定かつ高効率な量子もつれ光子対生成を実証した例として重要な成果である。

第4章では，特殊な分極反転プロファイルをもつ疑似位相整合素子を用いた周波数無相関光子対発生の実験結果について述べている。互いの周波数に相関をもたない光子対の発生は，高い純度の量子干渉性を有する伝令付単一光子を得るために必須の条件である。拡張位相整合の一種である群速度整合 SPDC を用いることにより，ほぼ周波数相関のない光子対を生成できることは以前より知られていたが，位相整合スペクトルが sinc 関数型の裾をもつため，周波数相関を完全になくすことは困難であった。本研究では，位相整合スペクトルがガウス関数型となるように分極反転のデューティ比を空間的に制御した PPKTP（PP-$KTiOPO_4$）素子を採用し，その位相整合スペクトルと 2 光子結合スペクトルを計測して，周波数相関および伝令付単一光子としての純粋度を定量的に評価した。その結果，この方法を用いることで非常に高い純度（0.99）の伝令付単一光子状態が生成可能であることを明らかにした。この結果は，人工的に制御された分極反転構造によって光子対の周波数相関を高度に制御可能であることを実証した例として，極めて重要な成果である。

第5章では，拡張位相整合導波路素子を用いた高効率周波数無相関光子対発生の実験結果について述べている。上述した群速度位相整合による周波数無相関光子対発生を高効率化するために，PPKTP 導波路素子を用いて光子対を発生し，生成効率と周波数相関，伝令付単一光子としての純度を評価した。その結果，高い純度（0.88）と生成効率（4.7×10^{9} $s^{-1}W^{-1}$）をもつ伝令付単一光子状態が生成可能であることを明らかにした。また，PPKTP 導波路構造では群速度整合波長が通信波長帯よりやや長波長側（>1.65 μm）にシフトすることを指摘した。さらに，強度相関関数（$g^{(2)}$）を用いた純度の評価を行って周波数相関から得た値と比較検討した結果，両者は定性的な傾向は一致するものの定量的には有意の差異があることを示した。この結果は，拡張位相整合導波路素子を用いた高効率周波数無相関光子対生成の有用性を示すとともに，従来の純粋度の評価方法には検討の余地があることを提起した点で重要な成果である。

第6章は結論である。

以上要するに本論文は，擬似・拡張位相整合自発パラメトリック下方変換素子を用いた高効率・高性能な光子対発生技術の研究開発について論じたものであって，電子工学，量子情報通信工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。